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14. ABSTRACT We present a global view of large-scale ionospheric disturbances during the main phase of a major geomagnetic storm. We find that the low-latitude, auroral, and polar latitude regions are coupled by processes that redistribute thermal plasma throughout the system. For the large geomagnetic storm on 20 Nov 2003, we examine data from the high-latitude incoherent scatter radars at Millstone Hill, Sondrestrom, and EISCAT Tromso, with SuperDARN HF radar observations of the high-latitude convection pattern and DMSP observations of in-situ plasma parameters in the topside ionosphere. We combine these with north polar maps of stormtime plumes of enhanced total electron content (TEC) derived from a network of GPS receivers. The polar tongue of ionization (TOI) is seen to be a continuous stream of dense cold plasma entrained in the global convection pattern. The dayside source of the TOI is the plume of storm enhanced density (SED) transported from low latitudes in the postnoon sector by the subauroral disturbance electric field. Convection carries this material through the dayside cusp and across the polar cap to the nightside where the auroral F region is significantly enhanced by the SED material. The three incoherent scatter radars provided full altitude profiles of plasma density, temperatures, and vertical velocity as the TOI plume crossed their different positions, under the cusp, in the center of the polar cap, and at the midnight oval/polar cap boundary. Greatly elevated F peak density ($>1.5 \times 10^{12} \text{ m}^{-3}$) and low electron and ion temperatures ($\sim 2500 \text{ K}$ at the F peak altitude) characterize the SED/TOI plasma observed at all points along its high-latitude trajectory. For this event, SED/TOI F region TEC (150-1000 km) was $\sim 50 \text{ TECu}$ both in the cusp and in the center of the polar cap. Large, upward directed fluxes of O^+ ($>1.0 \times 10^{14} \text{ M}^{-2} \text{ s}^{-1}$) were observed in the topside ionosphere from the SED/TOI.						
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Multiradar observations of the polar tongue of ionization

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[1] We present a global view of large-scale ionospheric disturbances during the main phase of a major geomagnetic storm. We find that the low-latitude, auroral, and polar latitude regions are coupled by processes that redistribute thermal plasma throughout the system. For the large geomagnetic storm on 20 November 2003, we examine data from the high-latitude incoherent scatter radars at Millstone Hill, Sondrestrom, and EISCAT Tromsø, with SuperDARN HF radar observations of the high-latitude convection pattern and DMSP observations of in situ plasma parameters in the topside ionosphere. We combine these with north polar maps of stormtime plumes of enhanced total electron content (TEC) derived from a network of GPS receivers. The polar tongue of ionization (TOI) is seen to be a continuous stream of dense cold plasma entrained in the global convection pattern. The dayside source of the TOI is the plume of storm enhanced density (SED) transported from low latitudes in the postnoon sector by the subauroral disturbance electric field. Convection carries this material through the dayside cusp and across the polar cap to the nightside where the auroral *F* region is significantly enhanced by the SED material. The three incoherent scatter radars provided full altitude profiles of plasma density, temperatures, and vertical velocity as the TOI plume crossed their different positions, under the cusp, in the center of the polar cap, and at the midnight oval/polar cap boundary. Greatly elevated *F* peak density ($>1.5 \times 10^{12} \text{ m}^{-3}$) and low electron and ion temperatures ($\sim 2500 \text{ K}$ at the *F* peak altitude) characterize the SED/TOI plasma observed at all points along its high-latitude trajectory. For this event, SED/TOI *F* region TEC (150–1000 km) was $\sim 50 \text{ TECu}$ both in the cusp and in the center of the polar cap. Large, upward directed fluxes of O^+ ($>1.0 \times 10^{14} \text{ m}^{-2} \text{ s}^{-1}$) were observed in the topside ionosphere from the SED/TOI plume within the cusp.

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1. Introduction

1.1. Tongue of Ionization (TOI)

[2] During disturbed conditions, rapid sunward convection from the postnoon midlatitude ionosphere carries high-density solar-produced *F* region plasma through the dayside cusp and into the polar cap. Knudsen [1974] investigated the effects of rapid antisunward convection on the polar *F* layer as it is convected through the cusp, over the polar cap, and into nightside auroral latitudes. That study solidified the suggestion of Sato [1959] of the existence of a “tongue” of ionospheric plasma (TOI) extending from the dayside to the nightside ionosphere, driven by cross polar cap electric fields. Foster [1984] examined the average diurnal pattern

of convection and *F* region density at auroral latitudes observed from Chatanika, Alaska. A tongue of enhanced density was seen to follow the convection contours toward the cleft and the polar cap from lower latitudes in the postnoon sector. It was conjectured that the high-density plasma seen entering polar latitudes at noon was convected rapidly antisunward across the polar cap where it contributed to the enhancement of *F* region plasma seen above 70°A near midnight. Foster [1989] reviewed radar observations which characterized the plasma streaming from low-latitudes as the source of the polar TOI.

[3] Sojka et al. [1993, 1994] presented model studies of the fragmentation of the ionization tongue into the discrete polar patches, and Crowley [1996] provided an overview of the characteristics of the patches and blobs observed at polar latitudes. These regions of enhanced ionization in the polar cap present a significant space weather problem [Schunk and Sojka, 1996] because of the plasma density irregularities that form along their borders [e.g., Keskinen and Ossakow, 1983; Tsunoda, 1988] producing a disturbed scintillation environment for communications links crossing the polar ionosphere. In addition, the dense *F* region plasma in the polar TOI and patches are a source for enhanced polar

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wind outflow on open magnetic field lines mapping into the magnetotail [Schunk and Sojka, 1997; Schunk et al., 2005].

1.2. Midlatitude Storm Enhanced Density (SED)

[4] The MIT Millstone Hill incoherent scatter radar (ISR), located at 55°N (invariant latitude) near the ionospheric projection of the plasmapause and the plasmasphere boundary layer (PBL) [Carpenter and Lemaire, 2004], regularly observes storm enhanced density (SED) in the pre-midnight subauroral ionosphere during the early stages of magnetic disturbances [Foster, 1993]. These high-TEC (total electron content) plumes of ionization are seen in the pre-midnight and afternoon sector at the equatorward edge of the main ionospheric trough and stream sunward carried by the low-latitude edge of the subauroral disturbance electric field (the subauroral polarization stream, SAPS [Foster and Burke, 2002; Foster and Vo, 2002]). Combining ground and space-based thermal plasma imaging techniques, Foster et al. [2002] demonstrated that one such ionospheric SED plume mapped into the low-altitude signature of a plasmasphere drainage plume associated with the stormtime erosion of the PBL. Foster et al. [2004] used direct observations of the sunward $\mathbf{E} \times \mathbf{B}$ advection to quantify the flux of ions carried to the noontime cusp F region ionosphere by the SED plume ($\sim 10^{26}$ ions/s).

1.3. Plasma Entry to Polar Latitudes

[5] Foster and Doupnik [1984] and Foster et al. [1985] used the high-latitude ISRs at Chatanika and Sondrestrom to examine the flow of low-latitude cold plasma through the cusp ionosphere and into the polar cap. Foster [1989] used Millstone Hill radar observations during a major storm on 31 January 1982, to examine the dayside plasma entry region and clearly observed a sunward convecting ionization feature extending along the equatorward edge of the postnoon trough and into the polar cap. Radar elevation scans intersected this feature, providing density/altitude profiles through the plasma tongue and mapping its local time/latitude behavior. Within the plasma tongue, F region TEC was enhanced by over a factor of 3 to a level of 75 TEC units ($75 \times 10^{16} \text{ m}^{-2}$), and peak densities of $2.5 \times 10^{12} \text{ m}^{-3}$ at 400 km altitude and convection into the polar cap at speeds in excess of 1500 m s^{-1} were observed. That study suggested that the plasma carried through the cleft from lower latitudes serves as a tracer of polar cap convection away from the cusp and cleft. Recent studies using the EISCAT radars [e.g., Pryse et al., 2004] have reached a similar conclusion that a latitudinally restricted region of enhanced densities at subauroral latitudes, distinct from the normal midlatitude ionosphere, is likely to be the source for the plasma entering the polar cap near noon.

[6] Anderson et al. [1988] examined the role of an equatorward expansion of the dayside convection boundary in entraining lower-latitude solar-produced plasma as a source population for the polar cap density patches. Discrete patches could be formed by transient bursts of magnetopause reconnection [Lockwood and Carlson, 1992] or reorientation of the dayside convection pattern associated with changes in IMF orientation [e.g., Valladares et al., 1998]. Roger et al. [1994] considered southern hemisphere observations of patch formation in the winter cusp, far from the sunlit ionosphere, and concluded that such patches must

be produced locally by processes acting on cusp or boundary layer field lines.

[7] Heelis et al. [1983] combined data from the Chatanika, Millstone Hill, and EISCAT radars with AE satellite observations of plasma drift velocity inside the polar cap to produce “snapshots” of the cross-polar cap convection, demonstrating its continuity from the cusp region near noon to midnight-sector auroral latitudes. Enhanced-density patches had been identified within the polar cap by Weber et al. [1984], and Weber et al. [1986] tracked such ionization patches flowing in the antisunward direction from the center of the polar cap to the edge of the nightside auroral oval. In a study of the nighttime F region density enhancements, which were consistently seen at different radar sites during solar maximum, de la Beaujardiere et al. [1985] concluded that this plasma was of solar-produced origin and had been convected across the polar cap from a sunlit source region on the dayside. Robinson et al. [1985] described the spreading of this enhanced F region density plasma exiting the polar cap along auroral latitudes, entrained in the sunward two-cell auroral convection. Crowley et al. [2000] traced convection trajectories linking polar patches to auroral-latitude plasma blobs and showed that the enhanced plasmas exited the polar cap near midnight and spread around auroral latitudes in the sunward convective flow.

[8] In 1983, the former Chatanika radar began operations in the near vicinity of the noontime cleft at Sondrestrom, Greenland. Kelly and Vickrey [1984] presented characteristics of the plasma flow into the polar cap in the vicinity of the cusp. Foster et al. [1985] used radar azimuth scans to determine the noontime convection and density patterns. As had been seen at Chatanika, a region of solar-enhanced ionization was observed to be carried through the cleft and into the polar cap by the postnoon convection cell. Detailed radar observations of E region density enhancements and F region electron temperatures, combined with direct satellite observations of precipitating particles, revealed that precipitation effects were confined to the near vicinity of the convection reversal and verified that the high-density plasma being carried into the polar cap was not locally produced by particle precipitation. A similar conclusion was reached by Buchau et al. [1985], who examined the F region ionization patches at polar cap latitudes.

[9] In this study we present for the first time complete, simultaneous mapping of the plasma density and convection patterns extending from the SED source region in the low-latitude dusk-sector ionosphere to the cusp, across the polar cap, and into the nightside auroral F region. We find the SED/TOI feature to be continuous and to be closely aligned with the independently determined convection streamlines. We use global GPS TEC mapping to characterize the SED and TOI features and combine SuperDARN HF radar and DMSP ion driftmeter observations to determine instantaneous high-latitude convection patterns. While the TEC-convection maps provide a global two-dimensional picture of high-latitude thermal plasma redistribution during this event, local high-resolution incoherent scatter radar observations are used to identify the altitude distributions and plasma characteristics of the SED/TOI plumes as they enter, cross, and exit the polar cap. Appropriate conditions for this study were realized during the height of the 20 November

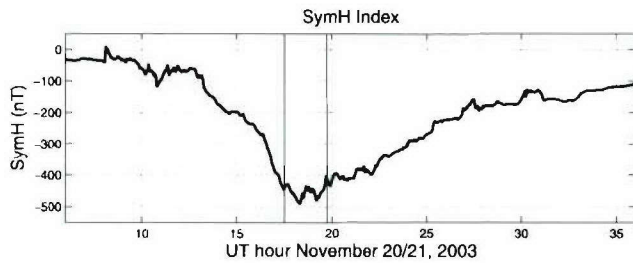


Figure 1. The interval of interest extends from 1730 through 2000 UT, immediately following a sharp drop in SymH (Dst).

2003 super storm (from 1730 UT until 2000 UT), after an interval of steeply declining Dst index (cf. Figure 1). Since little polar cap absorption occurred during the 20 November storm, strong SuperDARN HF backscatter returns were received from multiple local times at polar latitudes, permitting the polar convection pattern to be “imaged” while distributed GPS TEC observations mapped the evolution and extent of the SED and TOI enhancements.

2. Observations

2.1. GPS TEC Maps of Plasmasphere Erosion

[10] The satellites of the GPS constellation are in 12-hr circular orbits ($\sim 20,000$ -km altitude) with orbital inclination $\sim 55^\circ$, giving coverage to $L \sim 4$ from low-latitude receiving sites. The vertical TEC determined is the combined contribution of the ionosphere and overlying plasmasphere [Coster *et al.*, 2003]. For the severe disturbance event of 20 November 2003, we have determined 2-D maps of vertical TEC from a closely spaced network of ~ 450 North American GPS sites. Figure 2 presents such a map showing an intense SED plume with >150 TECu (1 TECu = $1.E16$ electrons/ m^2 , column density) extending NW across the northeastern USA and into Canada. The local time of this image (1945 UT) is ~ 1500 LT at Washington, D. C., which lies under the intense plume. During the 29–31 October 2003 superstorms [Foster and Rideout, 2005], similar dense plumes of SED spanned the United States, arising from regions of enhanced mid and low-latitude TEC as observed below 30° latitude in Figure 2.

2.2. Polar Convection Maps (SuperDARN and DMSP)

[11] The convection maps presented in this study were derived primarily from data from the northern hemisphere portion of the SuperDARN radar network and supplemented with data from the drift meters on DMSP spacecraft. SuperDARN, as described by Greenwald *et al.* [1995], is a multinational HF radar network capable of detecting backscatter from F region electron density irregularities that are produced by plasma instabilities. Ruohoniemi *et al.* [1987], among others, have shown that these irregularities are embedded in the F region plasma and drift at the plasma velocity. Thus Doppler information contained in the backscattered SuperDARN radar signals can be used to derive large-scale maps of ionospheric plasma convection.

[12] Under most conditions, the nine northern hemisphere SuperDARN radars operate continuously in scanning modes that provide $>75\%$ coverage of the auroral zone and polar

cap every 1–2 min. This particular day was devoted to Discretionary Operation and two of the radars were operated in a fixed-azimuth mode in support of ionospheric heating experiments over northern Norway. Also, because the high-latitude convection pattern was greatly expanded on 20 November, large portions of the convection pattern had expanded well equatorward of the fields of view of the radars. Although the polar cap portions of the convection patterns were still reasonably well specified, the lower latitude sunward convecting regions were largely missed in the SuperDARN coverage. For these reasons, we have supplemented the SuperDARN measurements with data from the drift meters on the DMSP spacecraft which provide important information on the equatorward boundary of the high-latitude convection cells and the nature of the sunward convecting flows. This information is critical for identifying the midlatitude ionospheric regions from which plasma is being extracted and brought into the polar cap.

[13] The global-scale convection patterns presented in this paper have been obtained from inversion techniques described by Ruohoniemi and Baker [1998]. The technique utilizes the full set of Doppler measurements provided by the SuperDARN radars in a particular hemisphere (northern for this study), other concurrent Doppler and/or drift velocity measurements (in this case, DMSP drift meter data), and supplemental model convection data commensurate with the IMF conditions of the study. The last data input is required to stabilize the solutions in regions where no data inputs are available. Shepherd and Ruohoniemi [2000] have concluded that the inclusion of the background model has little influence on the resultant fitted convection patterns in regions where there is good data coverage. When the radar coverage spans the dayside throat, the solution for the global potential variation becomes independent of the model contribution, and other features of the high dayside

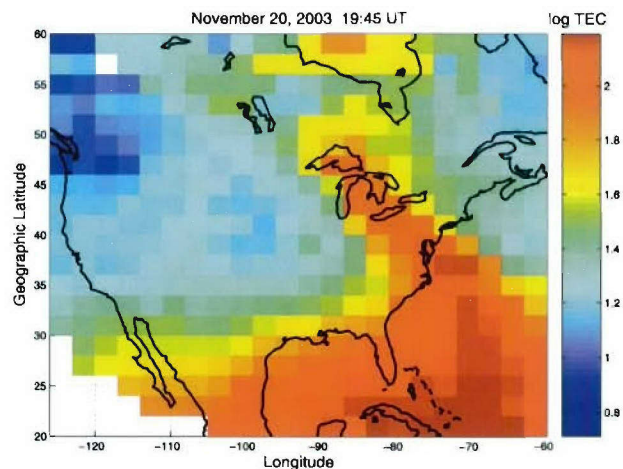


Figure 2. GPS vertical total electron content (TEC) observations over the continental USA at the height of the 20 November 2003 storm map an intense plume of storm enhanced density (TEC > 100 TECu) extending from a source region east of Florida, across the mid-Atlantic states, and into central Canada. Log10 TEC (TECu) is shown (1 TECu = $1.E16$ electrons/ m^2 , column density).

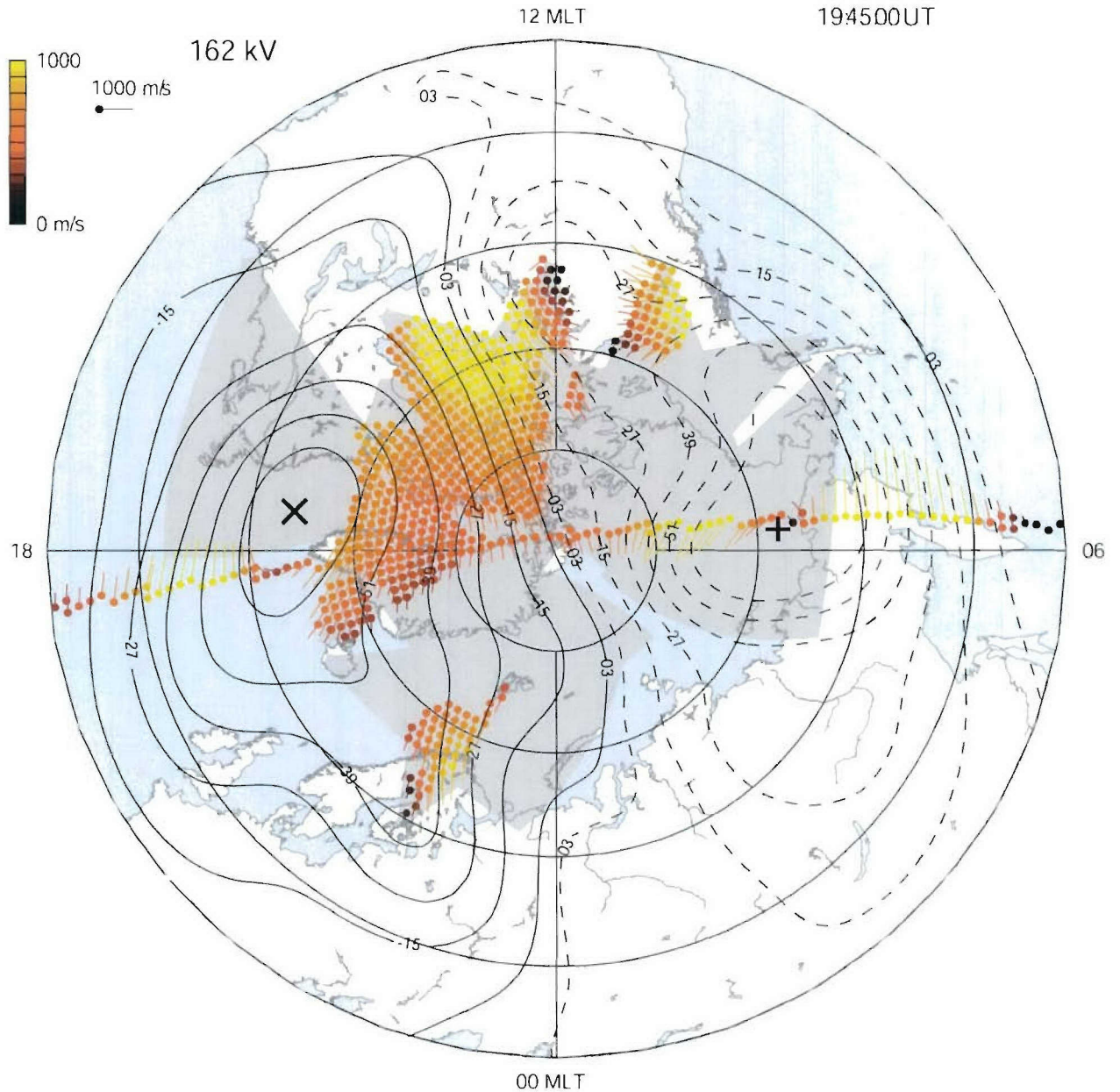


Figure 3. Convection vectors (see text) are plotted at the points of individual observations by DMSP F-13 and the SuperDARN radars near the time of the GPS TEC observations of Figure 2. Equipotential contours of the calculated convection pattern are shown in polar magnetic latitude/local times coordinates. Latitude circles are at 10° intervals.

pattern (e.g., location of cell centers) are very well determined.

[14] The SuperDARN data were collected in the standard operating mode, with each radar making a full scan every 2 min. For the convection maps, the data are fitted to an equiarea grid and averaged over a 20-min period. For the DMSP data, we took 20 min of the polar pass, and re-binned the DMSP measurements into the same grid we used for the SuperDARN data. In Figure 3 we present convection vectors derived from this fitting procedure

plotted at the points of the individual observations by DMSP and the SuperDARN radars at north polar latitudes near the time of the GPS TEC observations of Figure 2. SuperDARN data from the 20-min interval centered at 1945 UT are included, and the fields of view of the individual radars are shaded. The DMSP F13 north polar pass spanned 1956–2024 UT. The calculated convection pattern is shown in polar magnetic latitude/local times coordinates. Equipotential contours of the convection electric field are shown with the centers of the dusk (negative)

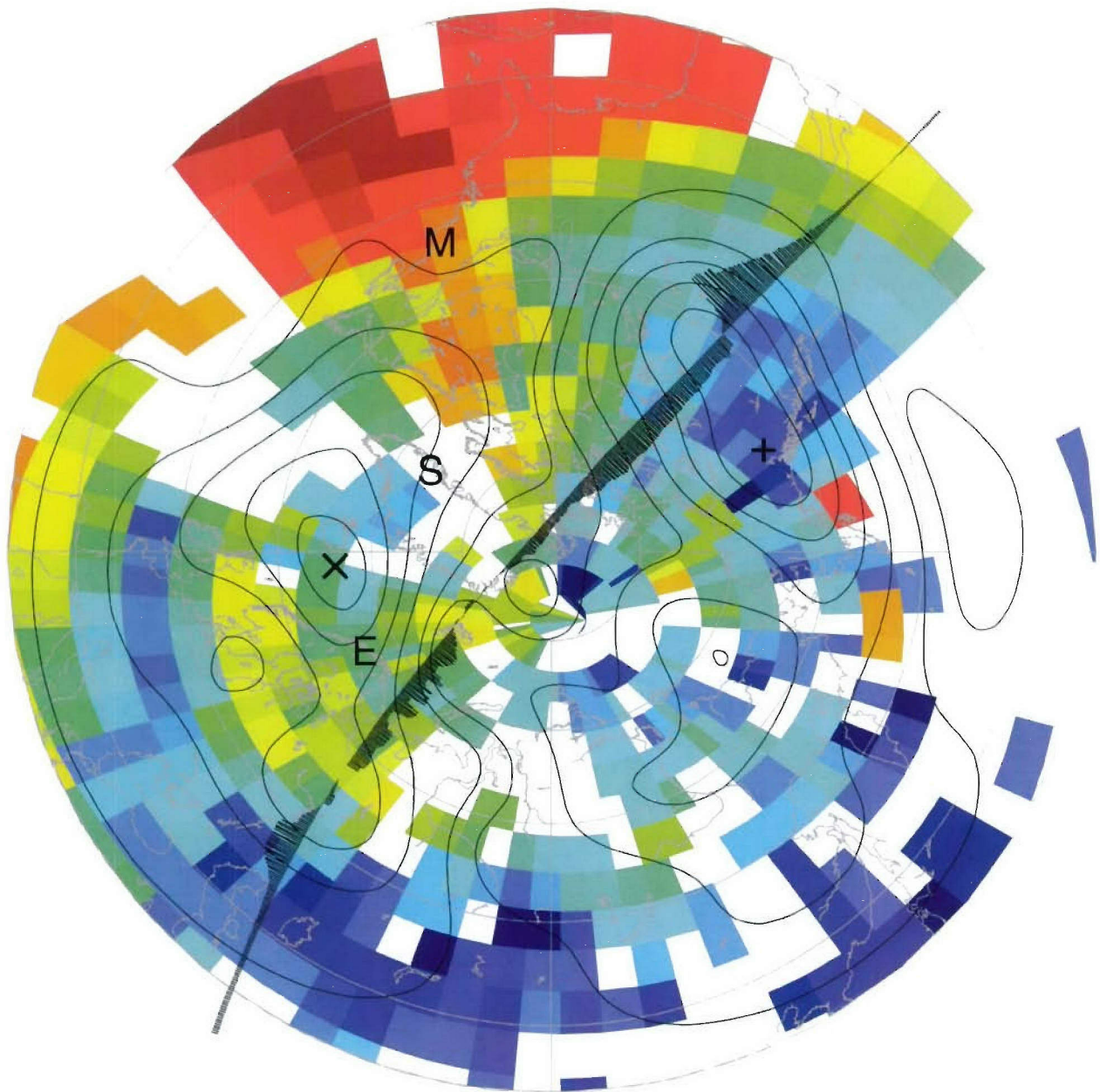


Figure 4. Combined GPS TEC and convection observations are displayed in polar projection (mag lat/MLT coordinates; 10-deg latitude circles; with noon at the top). The positions of the three IS radars are indicated (M, S, E). Using the log TEC color scale of Figure 2, data are shown for 1730 UT when the SED plume extended through the cusp convection convergence above the Millstone Hill ISR (M) near noon. Vertical TEC observations binned by lat/long at 350 km altitude are displayed with the simultaneous, independent convection pattern derived from combined SuperDARN and DMSP observations. Ion drift meter cross-track velocity data from a transpolar cap DMSP pass are shown, indicating antisunward convection above 60 deg latitude spanning the polar region.

and dawn (positive) potential cells indicated by “X” and “+” respectively. Excellent data coverage was obtained across the dayside polar cap entry region.

2.3. Combined Maps of Polar TOI and Convection

[15] We now consider global maps of ionospheric TEC for the 20 November 2003 storm interval and their relationship to the independently determined patterns of high-

latitude ionospheric plasma convection. TEC and convection maps are presented in a common, merged format for three times during the event, 1730 UT (Figure 4), 1820 UT (Figure 5), and 1945 UT (Figure 6), when the incoherent scatter radar facilities (see below) sampled the SED/TOI plume in different regions. Equipotential convection contours derived from merged SuperDARN HF backscatter observations and DMSP driftmeter measurements are pre-

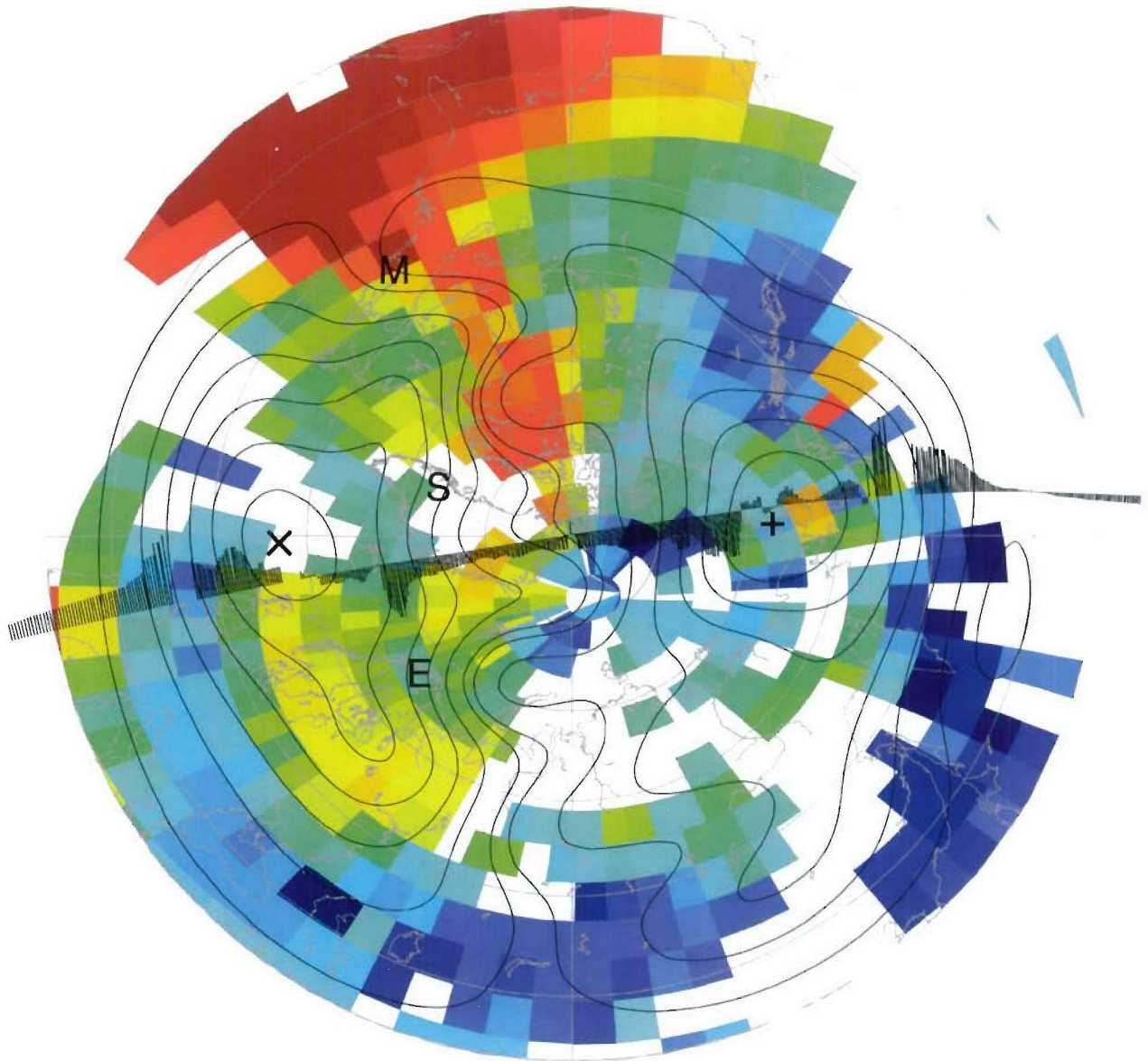


Figure 5. Polar mapping of the TOI at 1820 UT indicates that the enhanced SED plume closely followed the convection trajectory into polar latitudes near noon and across the polar cap to Sondrestrom (S). Data from a simultaneous DMSP F13 pass indicate that the TOI was centered in the antisunward polar cap convection flow at this time.

sented superimposed on the GPS TEC maps. Log₁₀ TEC is shown, using the color scale of Figure 2. Areas shown in white denote a lack of GPS TEC coverage at those points. Following the format of Figure 3, the merged maps are presented in magnetic latitude/local time coordinates with noon at the top of the figure. For later reference, the positions of the three operating incoherent scatter radars at Millstone Hill, Sondrestrom, and EISCAT Tromsø are indicated on each map (M, S, E).

[16] Both the SED and TOI are driven by the large-scale magnetospheric convection electric field whose general characteristics persist for many hours during major storms. Individual high-latitude ground-based observatories rotate with the Earth under the cold plasma features advected and redistributed around this flow pattern. Early in the event

(1730 UT), the Millstone Hill complex (M) lay under the dayside source of the SED/TOI plume in the vicinity of the noontime cusp. Figure 4 presents the combined TEC-convection map for this time in the format described above. Millstone Hill (M) lies near the dayside convection convergence (the cusp) and the TOI is seen to extend antisunward into the polar cap from a source equatorward of this point. The Millstone Hill radar vertical profiles at 1730 UT presented in section 2.4 describe the local characteristics of the SED plasma as it passes through the cusp ionosphere and enter the polar cap.

[17] In Figure 5 we display the merged TEC-convection map for 1820 UT, following the format of Figure 4. An overflight of the F13 satellite is shown and driftmeter data from this pass have been combined with the SuperDARN

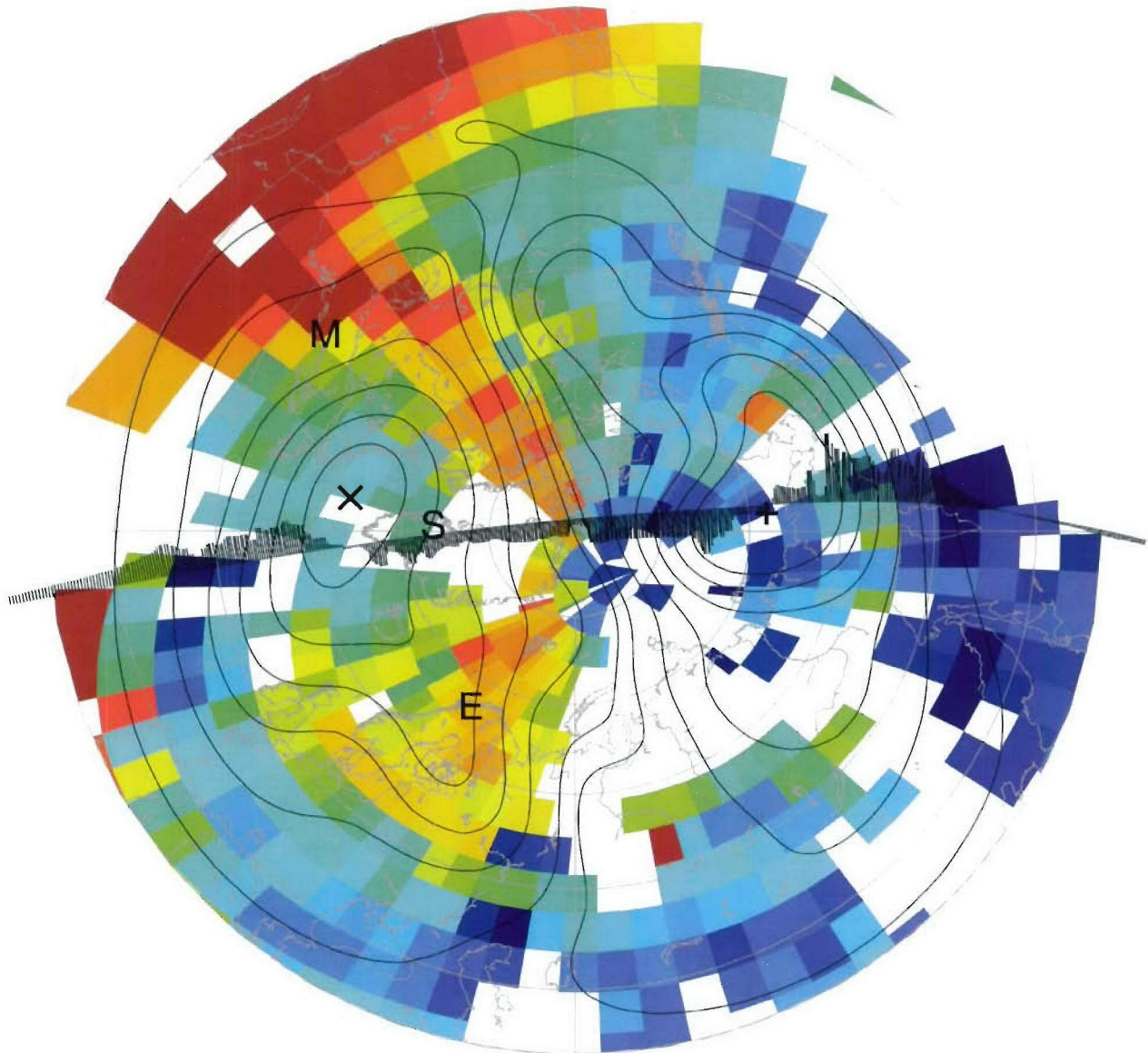


Figure 6. Polar projection of the TEC plume shown in Figure 2 is presented in the format of Figure 3. The SED/TOI plume is seen to extend continuously from its low-latitude source in the prenoon sector, through the dayside cusp and across the polar cap to the midnight sector over the EISCAT facility (E).

HF observations in determining the convection pattern superimposed on the TEC data. The enhanced SED plume closely follows the convection trajectory into polar latitudes near noon and across the polar cap to the vicinity of Sondrestrom (areas shown in white denote a lack of GPS TEC coverage at those points). The SAPS electric field responsible for PBL erosion and the formation of the SED plume at low latitudes in the dusk sector lies equatorward of the SuperDARN and convection-modeling field of view. The DMSP F13 data described below indicates that the SAPS at this time is centered near 45° maglat at 18 MLT). At that location, the strong sunward convection of the SAPS peak lies within the TEC depletion of the dusk-sector trough. Poleward of this ($\sim 55^\circ$ latitude) elevated TEC is seen within the return sunward auroral convection.

[18] The polar snapshot presented in Figure 6 for 1945 UT displays the continuity of the polar TOI from the dayside to

near midnight. The strong plume of SED seen in Figure 2 is swept across polar latitudes from its low-latitude source SE of Florida to a position equatorward of the EISCAT facility (E). Simultaneous DMSP observations of plasma drift indicate that the TOI lay in the center of the antisunward polar convection region. The TOI enhancement extends continuously into the nightside auroral region, exiting the polar region in the midnight sector over Scandinavia. Vertical profiles of ionospheric parameters within the TOI plume at the nightside auroral oval/polar cap boundary observed from the EISCAT facility at this time are presented in the following section.

2.4. Incoherent Scatter Radar Observations of the SED/TOI Plume

[19] Incoherent scatter radar (ISR) observations have been used to identify and define storm enhanced density

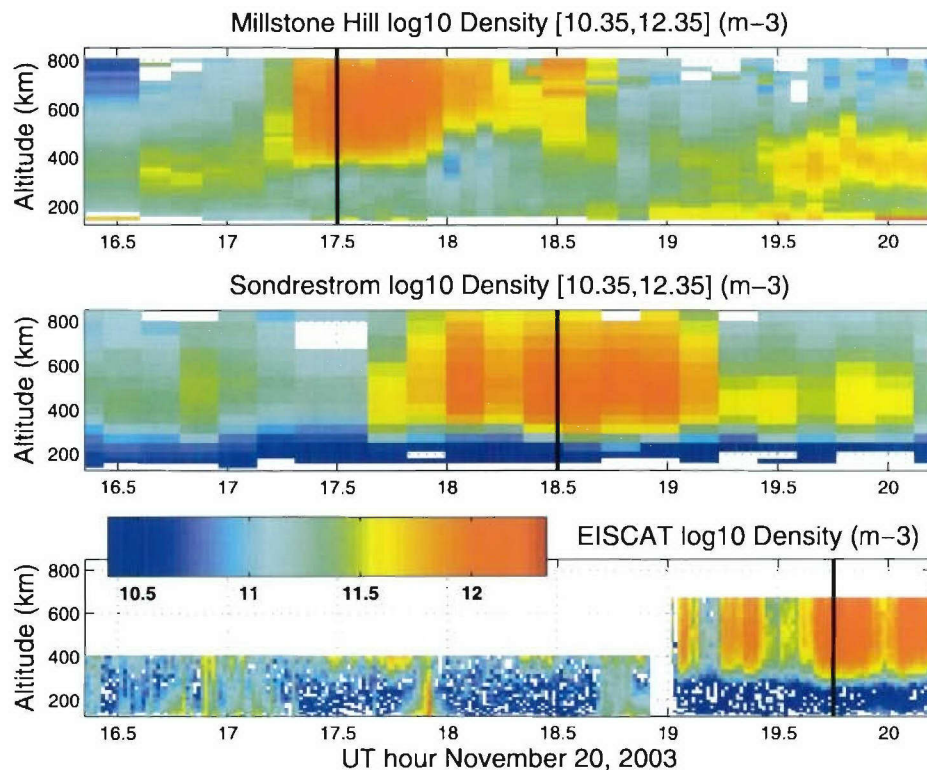


Figure 7. Vertical profiles of F region plasma density above the three high-latitude ISR facilities are shown for the 20 November 2003 event. Vertical black lines indicate times when the SED/TOI plume was sampled by each vertical radar beam. Millstone Hill observations at 1730 UT sampled the SED as it entered the dayside cusp. Sondrestrom (1830 UT) observed the TOI in the central polar cap. EISCAT Tromsø observed the TOI (1945 UT) as it exited the polar cap near midnight.

(SED) plasma near its midlatitude source [Foster, 1993]. Characteristics of the SED plasma at mid latitudes include enhanced F region TEC, an elevated F -peak altitude, low electron temperature, and a characteristic sunward velocity of ~ 800 m/s. For the 20 November 2003 event reported here, our observations indicate that such midlatitude SED was carried through the cusp and across the polar cap. The plume of low-energy SED plasma constitutes a dense ionospheric source for the processes operating on field lines in the cusp, polar cap, and nightside auroral region that interconnect the ionosphere to the overlying magnetosphere. It is important to determine the characteristics of the ionospheric plasma in these regions in order to understand and model these processes and their consequences. We use ISR observations to describe the evolution of the TOI plasma as it transits these varied regions and to provide altitude profiles of plasma parameters as a reference and input for models addressing the related processes.

[20] Responding to an alert forecasting a probable major geomagnetic disturbance, the northern high-latitude ISR facilities commenced a program of ionospheric observations in time to observe the onset and development of the major storming on 20 November 2003. The SED and polar tongue of ionization came into the radars' fields of view at various times and positions as the storm developed. In this paper we present for the first time ISR profiles of ionospheric parameters sampling the polar TOI near its noontime source, in mid polar cap, and in the midnight region where

the TOI exits polar latitudes. Vertical profiles of log plasma density above Millstone Hill, Sondrestrom, and EISCAT Tromsø are shown in Figure 7 at the times when the SED and polar tongue of ionization crossed their positions during this event. Vertical black lines indicate the times when the SED/TOI plume was being sampled directly by each vertical radar beam. Millstone Hill observations at 1730 UT sampled the SED as it entered the dayside cusp (cf. Figure 4). A rapid appearance of a dense topside plasma enhancement with an increase in the F peak height to >500 km was seen as the radar rotated under the plume near noon (1700 UT at Millstone Hill). This signature is that reported by Foster [1993] for noon-sector SED. Sondrestrom (1830 UT, 1630 MLT) observed the TOI in the center of the polar cap (see below). EISCAT Tromsø observed the TOI plasma after 1930 UT in the region where it exited polar latitudes near midnight (cf Figure 6). Each radar observed the TOI overhead for ~ 1 hour during the event as the plume of TOI evolved and the radar sites moved under its approximate noon-to-midnight orientation.

[21] Profiles of plasma density, vertical velocity, and ion and electron temperature for the SED/TOI plasmas seen from the three incoherent scatter radar facilities are presented in Figure 8 for the times indicated by the heavy lines in Figure 7. F -peak density exceeded $1.1 \times 10^{12} \text{ m}^{-3}$ at all sites with F peak altitudes between 400 and 500 km. The altitude of the F peak increased from ~ 300 to >500 km above Millstone Hill as that site sampled the SED plume as it

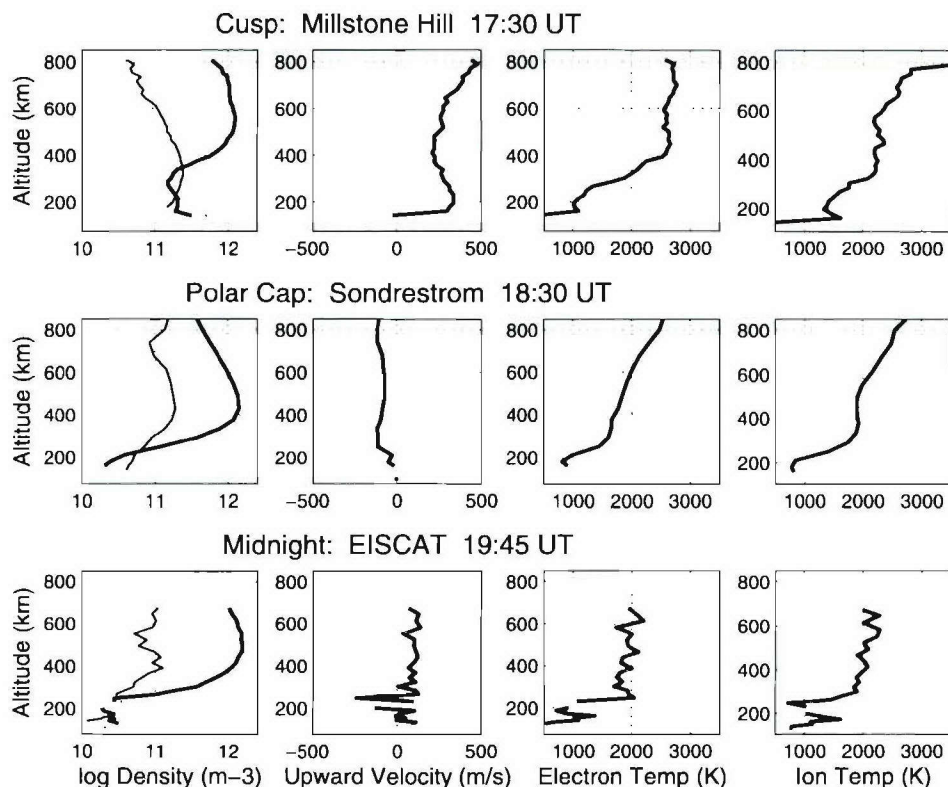


Figure 8. Vertical profiles of ionospheric density, velocity, and ion and electron temperature within the TOI are shown for observations from Millstone Hill (cusp, 1730 UT), Sondrestrom (polar cap, 1830 UT), and EISCAT (midnight, 1945 UT). Greatly elevated F peak density and low electron and ion temperatures characterize the SED/TOI plasma observed at all points along its high-latitude trajectory. F region uplift and strong ion outflow occur as the SED plume of low-latitude thermal plasma enters the cusp. An upward flux of O^+ ions in the cusp of $3.E14\text{ m}^{-2}\text{s}^{-1}$ at 650 km altitude was observed by the Millstone Hill ISR. F region TEC (150 – 1000 km) was 55 TECu over Sondrestrom.

entered the cusp. The topside profile observed from Millstone Hill at this time was relatively flat and the density remained $>1.E12\text{ m}^{-3}$ to altitudes above 700 km. Light lines included with the density profiles for each radar present a measure of the background density observed on that day at times when the TOI plume was not in the radar beam. At each location, the F peak density within the TOI was $\sim 10\times$ greater than background during this event. Electron and ion temperature profiles were unremarkable, with characteristic plasma temperatures of $\sim 2000\text{ K}$ to 2500 K at F peak altitudes. Upward velocity in the topside F region in the cusp ionosphere exceeded 350 m/s at 800 km altitude. This velocity is far below that needed for the topside ions to escape into the magnetosphere. The upward flux of oxygen ions at 650 km altitude observed with the zenith-directed antenna exceeded $1.E14\text{ ions m}^{-2}\text{s}^{-1}$ for 30 min as the Millstone Hill radar rotated through the cusp plume of SED. A maximum O^+ upward flux of $3.E14\text{ m}^{-2}\text{s}^{-1}$ was seen, a value $10\times$ greater than that reported by Yeh and Foster [1990] for the 8 February 1986 superstorm for the upward flux of O^+ in the region of very strong frictional heating at midlatitudes. Additional acceleration mechanisms acting on the topside ionosphere near the cusp would be needed if a portion of this flux were to be injected into the magnetotail lobe. At the other ISR sites, F region vertical

velocities within the TOI at the altitudes of the radar observations were small ($<100\text{ m/s}$).

[22] The Sondrestrom Radar is located near the west coast of Greenland, just north of the Arctic Circle (geographic 66.99°N and 50.95°W), and is positioned within the nighttime polar cap and under the noontime cusp/cleft region for an average auroral oval [Kelly *et al.*, 1995]. The fully steerable antenna allows for the measurement of ionospheric plasma profiles (Ne, Te, Ti, and Vi) and height-resolved electrodynamics, as well as two-dimensional maps of the plasma distribution. In Figure 8 we present vertical plasma profiles observed at $\sim 1830\text{ UT}$ as the TOI plume crossed over the Sondrestrom IS radar, well within the polar cap (cf. Figure 5). F peak height above 400 km and F peak density $>1.5E12\text{ m}^{-3}$ were also seen at this position. F region total electron content (150–1000 km altitude) exceeded 55 TECu within the TOI. Again, in this position, the TOI plasma was characterized by unperturbed electron temperatures ($T_e \sim 2000\text{ K}$ at the 450-km F peak altitude) with electron and ion temperatures nearly equal. There was no evidence of strong topside polar wind outflow [cf. Schunk *et al.*, 2005] from the TOI plume in this location, a downward velocity of $\sim 100\text{ m/s}$ was seen at all heights sampled.

[23] Intermittently, the Sondrestrom radar performed N-S elevation scans which transected the TOI plume. Data from

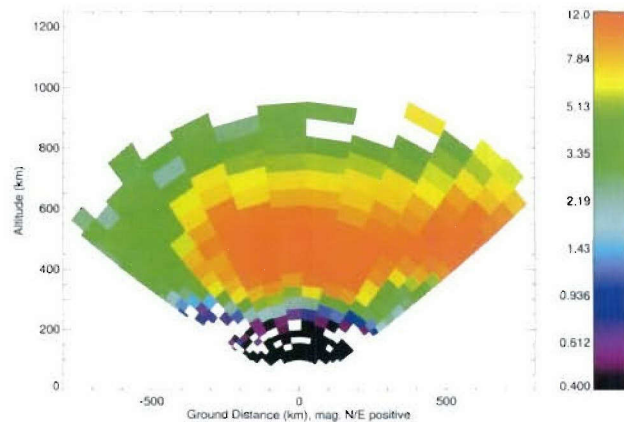


Figure 9. Sondrestrom ISR elevation scans identified the cross-plume extent and intensity of TOI at the time of the observations presented in Figures 7 and 8.

a scan at 1815 UT are presented in Figure 9. This cross section of the TOI accentuates the elevated F peak altitude (>400 km) and the >800 km cross-plume width of the TOI, consistent with the width of the TEC plume at mid polar latitudes shown in Figure 5. The combination of SuperDARN and ISR radar observations with GPS TEC mapping and DMSP *in situ* data presents a detailed picture of the characteristics of the TOI during this highly disturbed event.

[24] On the nightside, the enhanced TEC carried across the polar cap in the TOI was seen to spread out along the sunward return convection of (primarily) the dusk-sector convection cell (cf. Figures 5 and 6). This is in keeping with the suggestions and modeling of, e.g., *Robinson et al.* [1985] and *Crowley et al.* [2000]. The EISCAT Tromsø ISR facility was situated in the region where the TOI exited the polar cap at 1945 UT. The EISCAT profiles of Figure 8 indicate that the TOI F peak density was still in excess of $1.0 \times 10^{12} \text{ m}^{-3}$ as the plasma exited into the nightside auroral latitude region. Ion and electron temperature were nearly equal (~ 2000 K) through the F region and the vertical velocity was small and upward. The EISCAT profiles (Figures 7 and 8) give no evidence of an E region density enhancement nor the elevated (>4000 K) electron temperatures which would accompany auroral particle precipitation, indicating that the EISCAT profiles of Figure 8 were obtained just poleward of the auroral boundary.

[25] For this strong event the ISR observations from the three sites indicate that the SED/TOI plasma maintained $>1.0 \times 10^{12} \text{ m}^{-3}$ density and low electron temperature at all locations as it was convected across polar latitudes from its dayside source. The TEC observations of Figure 6 indicate that TEC within the TOI was fairly constant (~ 50 TECu) along its cross-polar cap convection trajectory at that time. TEC in the midlatitude source region (cf. Figure 2) was >100 TECu at that time.

2.5. DMSP Overflights of the Disturbed Ionosphere

[26] DMSP transpolar overflights have long been used to identify and characterize topside density enhancements in mid polar cap. Multiparameter DMSP F13 observations for the pass whose trajectory is displayed on Figure 5 are presented in Figure 10. The poleward boundaries of

auroral precipitation (middle panels) are clearly seen near 70° maglat at both 1800 MLT (1824 UT) and at 0700 MLT (1835 UT). Antisunward cross-track convection spans the polar cap between these two points (lower panel). A TOI density enhancement is seen centered at ~ 1827 UT where the DMSP trajectory intersects the TEC plume shown in Figure 5 over eastern Greenland. For reference, the SAPS convection which drives the SED sunward convection on the dayside is seen at subauroral latitude near 45° maglat (1818 UT).

3. Discussion

[27] We present a global view of large-scale ionospheric disturbances during the main phase of a major geomagnetic storm. We find that the low-latitude, auroral, and polar latitude regions are coupled by processes which redistribute thermal plasma throughout the system. Multi-instrument observations of TEC and convection for this event depict the formation and characteristics of the tongue of ionization which spans polar latitudes from a source in the dayside midlatitude ionosphere, through the dayside cusp, and across the polar cap to auroral latitudes in the midnight sector. The polar TOI is seen as a continuous stream of dense cold ionospheric plasma entrained in the global convection pattern. The dayside source of the TOI is the plume of storm enhanced density (SED) transported toward noon from subauroral latitudes by the SAPS disturbance electric field. Transpolar cap flow carries this plasma to the nightside where the auroral F region is greatly enhanced by the SED material.

[28] For the 20 November 2003 event, the high-latitude incoherent scatter radars provide detailed profiles of ionospheric plasma parameters at various points within the SED/TOI feature. These profiles characterize the disturbed polar environment within which irregularity growth, scintillations, and polar wind outflow occur. Considerable uplift of the F region plasma is seen as the SED plume enters the polar region near noon, in agreement with the Chatanika radar findings of *Foster and Doupnik* [1984]. Modest electron temperatures ($T_e \sim 2500$ K) are observed within the TOI plasma at polar latitudes, in agreement with the characteristics of midlatitude SED reported by *Foster* [1993].

[29] The appearance of an intense tongue of ionization in the center of the polar cap over Sondrestrom is not unique to the 20 November 2003. During the 29/30 October 2003 storm, similar conditions existed and a dense TOI plume was sampled by the Sondrestrom ISR. At 2325 UT (~ 20 MLT) on 29 October 2003, F region density within the TOI plume exceeded $1.0 \times 10^{12} \text{ m}^{-3}$ between 300 km and 800 km altitude, with F peak density $3.0 \times 10^{12} \text{ m}^{-3}$ at 500 km. Vertical F region TEC was 130 TECu (150–1000 km altitude) and an O^+ upward flux of $3.0 \times 10^{14} \text{ m}^{-2} \text{ s}^{-1}$ was observed at the F peak altitude. During that event the upward velocities increased with altitude through the topside.

[30] Our observations of the 20 November 2003 event show that a continuous channel of high-density, high TEC cold plasma streamed through the cusp ionosphere, the central polar cap, and through the midnight-sector convection divergence region. *Foster* [1993] has presented a preliminary statistical study of the occurrence of SED which

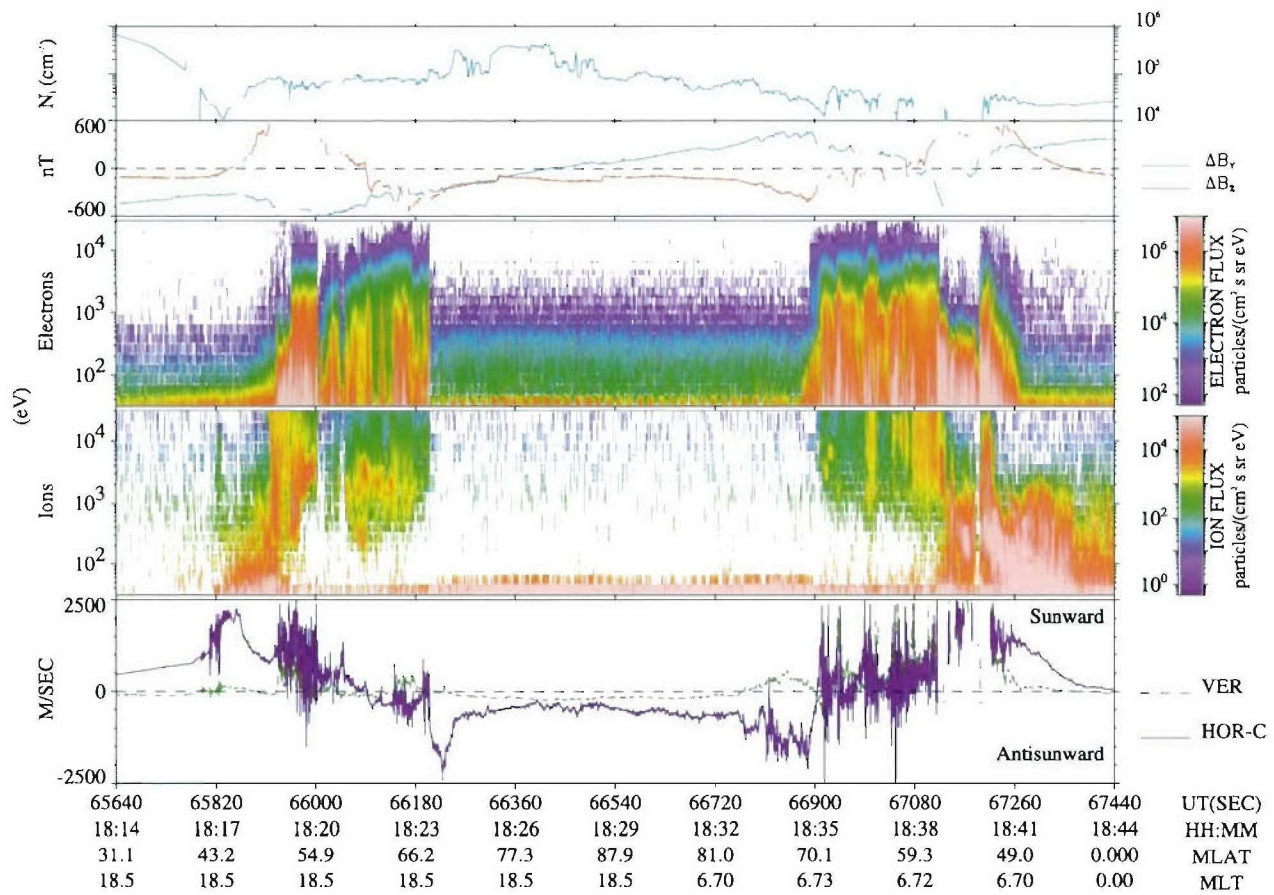


Figure 10. DMSP F13 provided in situ observations of SAPS (1817 UT) and TOI (seen between 1824–1828 UT) during the overflight of the north polar region presented in Figure 4.

indicates that it is present in the postnoon American sector for all $Kp > 3$ (the driving SAPS electric field has similar occurrence statistics [Foster and Vo, 2002]). Foster et al. [2004] find a flux of $\sim 10^{26}$ ions s^{-1} carried into the cusp ionosphere by the SED plumes. Large, upward directed fluxes of O^+ ($> 1.0 \times 10^{14} m^{-2} s^{-1}$) have been observed in the topside ionosphere both from the SED within the cusp and from the TOI on polar cap field lines. The streaming SED/TOI thermal plasma we have described provides a source population for any ion outflow or acceleration mechanisms acting on the topside ionosphere in the cusp, polar cap, or midnight auroral regions, and in so doing can contribute to the outflow of ionospheric species onto magnetospheric field lines.

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References

- Anderson, D. N., J. Buchau, and R. A. Heelis (1988), Origin of density enhancements in the winter polar cap ionosphere, *Radio Sci.*, **23**, 513.
- Buchau, J., E. J. Weber, D. N. Anderson, H. C. Carlson Jr., J. G. Moore, B. W. Reinisch, and R. C. Livingston (1985), Ionospheric structures in the polar cap: Their origin and relation to 250-MHz scintillation, *Radio Sci.*, **20**, 325.
- Carpenter, D. L., and J. Lemaire (2004), The plasmasphere boundary layer, *Ann. Geophys.*, **22**(12), 4291–4298.
- Coster, A. J., J. Foster, and P. Erickson (2003), Monitoring the ionosphere with GPS: Space weather, *GPS World*, **14**(5), 42.
- Crowley, G. (1996), *Critical Review on Ionospheric Patches and Blobs*, *The Review of Radio Science*, vol. 1, Oxford Univ. Press, New York.
- Crowley, G., A. J. Ridley, D. Deist, S. Wing, D. J. Knipp, B. A. Emery, J. Foster, R. Heelis, M. Hairston, and B. W. Reinisch (2000), The transformation of high-latitude ionospheric *F*-region patches into blobs during the March 21, 1990 storm, *J. Geophys. Res.*, **105**, 5215.
- de la Beaujardiere, O., V. B. Wickwar, G. Caudal, J. M. Holt, J. D. Craven, L. A. Frank, L. H. Brace, D. S. Evans, J. D. Winningham, and R. A. Heelis (1985), Universal time dependence of nighttime *F* region densities at high latitudes, *J. Geophys. Res.*, **90**, 4319.
- Foster, J. C. (1984), Ionospheric signatures of magnetospheric convection, *J. Geophys. Res.*, **89**, 855.
- Foster, J. C. (1989), Plasma transport through the dayside cleft: A source of ionization patches in the polar cap, in *Electromagnetic Coupling in the Polar Clefts and Caps*, edited by P. Sandholt and A. Egeland, pp. 343–354, Kluwer Acad., Norwell, Mass.
- Foster, J. C. (1993), Storm-time plasma transport at middle and high latitudes, *J. Geophys. Res.*, **98**, 1675.
- Foster, J. C., and W. J. Burke (2002), SAPS: A new characterization for sub-auroral electric fields, *Eos Trans. AGU*, **83**, 393.
- Foster, J. C., and J. R. Doupnik (1984), Plasma convection in the vicinity of the dayside cleft, *J. Geophys. Res.*, **89**, 9107.
- Foster, J. C., and W. Rideout (2005), Midlatitude TEC enhancements during the October 2003 superstorm, *Geophys. Res. Lett.*, **32**, L12S04, doi:10.1029/2004GL021719.

- Foster, J. C., and H. B. Vo (2002), Average characteristics and activity dependence of the subauroral polarization stream, *J. Geophys. Res.*, **107**(A12), 1475, doi:10.1029/2002JA009409.
- Foster, J. C., J. M. Holt, J. D. Kelly, and V. B. Wickwar (1985), High resolution observations of electric fields and *F*-region plasma parameters in the cleft ionosphere, *The Polar Cusp*, edited by J. A. Holtet and A. Egeland, p. 349, Springer, New York.
- Foster, J. C., A. J. Coster, P. J. Erickson, J. Goldstein, and F. J. Rich (2002), Ionospheric signatures of plasmaspheric tails, *Geophys. Res. Lett.*, **29**(13), 1623, doi:10.1029/2002GL015067.
- Foster, J. C., A. J. Coster, P. J. Erickson, F. J. Rich, and B. R. Sandel (2004), Stormtime observations of the flux of plasmaspheric ions to the dayside cusp/magnetopause, *Geophys. Res. Lett.*, **31**, L08809, doi:10.1029/2004GL020082.
- Greenwald, R. A., et al. (1995), DARN/SuperDARN: A global view of high-latitude convection, *Space Sci. Rev.*, **71**, 763.
- Heelis, R. A., J. C. Foster, O. de la Beaujardiere, J. M. Holt, and E. Neilsen (1983), Multi-station measurements of high latitude ionospheric convection, *J. Geophys. Res.*, **88**, 10,111.
- Kelly, J., and J. Vickrey (1984), *F*-region ionospheric structure associated with antisunward flow near the dayside polar cusp, *Geophys. Res. Lett.*, **1**(9), 907.
- Kelly, J. D., C. J. Heinselman, J. F. Vickrey, and R. R. Vondrak (1995), The Sondrestrom radar and accompanying ground-based instrumentation, *Space Sci. Rev.*, **71**(1–4), 797.
- Keskinen, M. J., and S. L. Ossakow (1983), Theories of high latitude ionospheric irregularities, *Radio Sci.*, **18**, 1077.
- Knudsen, W. C. (1974), Magnetospheric convection and the high-latitude *F2* ionosphere, *J. Geophys. Res.*, **79**, 1046.
- Lockwood, M., and H. C. Carlson Jr. (1992), The production of polar cap electron density patches by transient magnetopause reconnection, *Geophys. Res. Lett.*, **19**, 1731.
- Pryse, S. E., R. W. Sims, J. Moen, L. Kersley, D. Lorentzen, and W. F. Dcng (2004), Evidence for solar production as a source of polar-cap plasma, *Ann. Geophys.*, **22**(4), 1093.
- Robinson, R. M., R. T. Tsunoda, J. F. Vickrey, and L. Guerin (1985), Sources of *F*-region ionization enhancements in the nighttime auroral zone, *J. Geophys. Res.*, **90**, 7533.
- Roger, A. S., M. Pinnock, J. R. Dudeney, K. B. Baker, and R. A. Greenwald (1994), A new mechanism for polar patch formation, *J. Geophys. Res.*, **99**, 6425.
- Ruohoniemi, J. M., and K. B. Baker (1998), Large-scale imaging of high-latitude convection with Super Dual Auroral Radar Network HF radar observations, *J. Geophys. Res.*, **103**, 20,797.
- Ruohoniemi, J. M., R. A. Greenwald, K. B. Baker, J.-P. Villain, and M. A. McCready (1987), Drift motions of small-scale irregularities in the high-latitude *F* region: An experimental comparison with plasma drift motions, *J. Geophys. Res.*, **92**, 4553.
- Sato, T. (1959), Morphology of ionospheric *F2* disturbances in the polar regions, A linkage between polar patches and plasmaspheric drainage plumes, *Rep. Ionos. Res. Space Res. Jpn.*, **13**, 91.
- Schunk, R. W., and J. J. Sojka (1996), Ionosphere-thermosphere space weather issues, *J. Atmos. Terr. Phys.*, **58**, 1527.
- Schunk, R. W., and J. J. Sojka (1997), Global ionosphere-polar wind system during changing magnetic activity, *J. Geophys. Res.*, **102**, 11,625.
- Schunk, R. W., H. G. Demars, and J. J. Sojka (2005), Propagating polar wind jets, *J. Atmos. Solar-Terr. Phys.*, **67**, 357.
- Shepherd, S. G., and J. M. Ruohoniemi (2000), Electrostatic potential patterns in the high-latitude ionosphere constrained by SuperDARN measurements, *J. Geophys. Res.*, **105**, 23,005.
- Sojka, J. J., M. D. Bowline, R. W. Schunk, D. T. Decker, C. E. Valladares, R. Sheehan, D. A. Anderson, and R. A. Heelis (1993), Modeling polar cap *F*-region patches using time varying convection, *Geophys. Res. Lett.*, **20**, 1783.
- Sojka, J. J., M. D. Bowline, and R. W. Schunk (1994), Patches in the polar ionosphere: UT and seasonal dependence, *J. Geophys. Res.*, **99**, 14,959.
- Tsunoda, R. T. (1988), High latitude *F* region irregularities: A review and synthesis, *Rev. Geophys.*, **26**, 719.
- Valladares, C. E., D. T. Decker, R. Sheehan, D. N. Anderson, T. Bullett, and B. W. Reinisch (1998), Formation of polar cap patches associated with north-to-south transitions of the interplanetary magnetic field, *J. Geophys. Res.*, **103**, 14,657.
- Weber, E. J., J. Buchau, J. G. Moore, J. R. Sharber, R. C. Livingston, J. D. Winningham, and B. W. Reinisch (1984), *F* layer ionization patches in the polar cap, *J. Geophys. Res.*, **89**, 1683.
- Weber, E. J., J. A. Klobuchar, J. Buchau, H. C. Carlson Jr., R. C. Livingston, O. de la Beaujardiere, M. McCready, J. G. Moore, and G. J. Bishop (1986), Polar cap *F* layer patches: Structure and dynamics, *J. Geophys. Res.*, **91**, 12,121.
- Yeh, H.-C., and J. C. Foster (1990), Storm-time heavy ion outflow at mid-latitudes, *J. Geophys. Res.*, **95**, 7881.
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